TEST PROGRAM FOR DETERMINATION OF REFLECTED PRESSURES IN ACCEPTOR BAYS

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ABSTRACT: Criteria for protection of personnel in DOE facilities requires that, for Class II explosives operations, all personnel in occupied areas other than the bay of occurrence not be exposed to overpressures greater than 15 psi. Several of the operating bays used at DOE facilities are World War II-era structures consisting of two or three wall cubicles with a "soft" roof. Of particular concern are bays which have a clay tile wall adjacent to the open front. A test program was initiated to determine the pressures reflected by this wall from a detonation in a donor bay into an adjacent bay. A 1/8th scale steel model of two adjacent bays was built, instrumented and tested to determine these pressures. Charge and gage locations were varied to determine relationships between pressure and scaled distance from a reflecting surface. Variations in scaled weight of the wall were used to determine reflectance effects. Test program, model fabrication, and results are discussed.

INTRODUCTION

A test program was initiated to determine overpressures reflected into adjacent occupied areas by an accidental detonation in an explosives operations bay. An overstrong steel model was built to model donor and acceptor bays to verify compliance with protection criteria. In the first phase of the program, a rigid steel wall was used to create a worst case configuration for measuring the maximum pressures reflected into the adjacent bay. The second phase of the program incorporated frangible reflecting walls to produce reflected pressures more representative of the conditions in the structure.

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BACKGROUND

Department of Energy (DOE) criteria requires that, for Class II operations, all personnel in occupied areas, other than the bay of occurrence, be protected from overpressures greater than 15 psi. Several explosives operating facilities are in use today which are in excess of 40 years old. These facilities were designed to conform to criteria which was not as stringent as that required today. Facilities which cause particular concern are those with adjacent operating bays with open front walls and a connecting corridor as shown in Figure 1. The corridor is composed of a concrete floor slab, clay tile exterior wall and a "soft" roof. The bays are two and three wall cubicles with 12" reinforced concrete walls. Roofs are either reinforced concrete or asbestos cement panels. A typical three wall bay is 19 ft. wide, 17.5 ft. high, and 23.5 ft. deep. "Thru" bays are 48 ft. deep two wall cubicles (open front and rear).

Explosives limits in the bays are 12 lbs. of high explosives (HE). A typical operating bay contains several operations with small quantities of explosives. The design charge weight for determining overpressures is taken as the entire bay limit converted to TNT using an equivalency factor. This yields a conservative predictions of overpressure but allows maximum flexibility for the operations. The Design Basis Accident (DBA) is a handling error occurring at any location within the bay which is more than three feet from any wall.

TEST PROGRAM

Description of Model

The 1/8th scale model used in the program was designed to remain elastic under the design loading to allow a large number of tests to be conducted. The model was constructed of A36 steel with welded and bolted (A307) connections. A plan view of the model is shown in Figure 2. The 1/2" floor plate was connected to 1/4"x 6" continuous plates on 6" centers to allow access to gage mounting holes. The 1/2" front wall was bolted to the floor and the 1/4" roof plate to allow removal. This provided a method for determining "wrap-around" pressures without the effects of a reflecting front wall. The roof was also bolted to the 1-1/2" side walls to allow testing of the model as a three wall cubicle without a roof. The back wall of the donor bay was bolted to allow modeling as a "thru" bay.

Gage mounting holes were provided at four locations in the floor along the front of the donor bay and at the front, 1/4 point, and center of the acceptor bay to measure side-on pressures. Six inch angles were bolted to the floor of the acceptor bay with pressure

gages installed at 3" above the floor to measure reflected pressures at each gage line. Gages were installed in the front wall at eight locations to measure reflected pressures 3" above the floor. The 3 inch measurement was equivalent to 2 feet in the full scale structure. The model was placed in an 11 ft. diameter test fire chamber before testing began. This permitted tests to be run in all weather conditions.

Instrumentation

Pressure gages were PCB Model 102A02, high resolution transducers with built-in amplifier. The gages were installed flush with the mounting surface and covered with an opaque material to protect against flashes from the detonation. All gages performed well during testing and appeared to sustain no appreciable damage during the tests. The gages are rated for 0-100 psi but will remain functional up to 1000 psi. The highest pressures measured during testing were less than 170 psi. The gages were coupled to a Neff Model 122 DC amplifier with a PCB Model 483A power unit and Beldon RG58-AU cabling. Signals from the amplifier were fed into a Sangamo 80, 14 channel magnetic tape recorder operating at 120 ips. The analog signal for each channel was digitized at 200 samples per millisecond using a Biomation Model 8100 Digital Waveform Recorder. The digitized voltages were recorded on magnetic disk and converted to pressure values using calibration voltage data and an HP 9845 computer. Pressure data was plotted using a thermal plotter. A typical pressure plot is shown in Figure 3.

Test Plan

Phase I

The high explosive used for each test was a single pressed, cylindrical charge of LX-10 weighing 10.64 grams with a diameter of 0.75" (L/D=1.05). This explosive has a TNT equivalency of 1.1. An RP-2 detonator was used to detonate the HE. The orientation of the charge was varied in the first four tests to determine directional effects of the cylindrical charge and detonator. End effects from the cylinder were negligible in the confined model, based on pressure measurements, and detonator effects were limited to an increase in reflected pressures from the back wall. It was determined that a forward orientation with the detonator at the rear would be used because the accident scenario was a handling error not involving a detonator.

Several model configurations were used to determine the effects of distance and reflective surfaces. The charge locations for the

test program are shown in Figure 4. Initially the charge was placed in the center of the donor bay and reflected pressures were measured at the reflecting wall and the face of the acceptor bay. Measured pressures were compared to predicted pressures to verify that results were within the range for which the gages had been calibrated. Results of these comparisons were used to modify the prediction of a calibration pressure range for each gage location.

Three gage lines were used in the acceptor bay to establish side-on and reflected pressures at various obliquities and distances from the reflecting wall. These lines covered the front half of the bay and were used to describe pressure contours for the bay. The front wall and roof were removed for some of the test shots to allow separation of "wrap around" pressures from the reflected pressures caused by the front wall.

The first phase of the program was designed to determine worst case effects for pressures reflecting off of a rigid wall. Fifty tests were conducted in the first phase. This rigid wall configuration produced pressures in the acceptor bay which were slightly above the 15 psi maximum. Phase II was initiated to determine a more accurate picture of the reflected pressures by substituting frangible walls of various densities for the rigid reflecting wall.

Phase II

The second phase of the program consisted of 10 test shots with three wall types and three charge locations. The first type tested was a wall composed of two layers of 6 mil polyethylene clamped to the front of the model with 1x4 blocking and bolts. This material was used for two tests to determine how much pressure would be reflected from an essentially massless wall. The charge was placed at the center of the bay for the first test and an equivalent of six feet from the front of the bay for the second test.

The second type of wall used in Phase II was 1/4" plywood. This was held in place with 1x4 blocking and bolted to the model. Two tests were also conducted for this type with the charge locations the same as for the polyethylene tests.

Gypsum board was use for the third wall type. This material was chosen to closely model the scaled weight of the clay tile wall in the structures of interest. The weight of the clay tile is 31 pounds per square foot of wall surface (psf). Two layers of 1/2" gypsum weighing approximately four psf were used to give an equivalent velocity in the scale model. This would reflect the same peak pressures into the acceptor bay in the scale model as

the clay tile wall would produce in the actual structure. This material was supported at the bottom by 1x4 blocking bolted to the floor. For the first test, the top of the gypsum board was nailed at three inches on center to 1x6 blocking which was bolted to the roof of the model. For the second test half of the nails were removed. The remaining four tests used a single nail in the top. This fastening method was used to model the weak supports for the clay tile wall.

RESULTS

Pressure Measurements

Peak pressures were read directly from the plotted traces. Since only the maximum pressures were of interest, with respect to the criteria, impulses were not computed. A summary of the measured pressures in Phase I for a charge in the center of the donor bay is given in Table 1.

Four locations were provided along each gage line to allow comparisons of measured values in close proximity to each other. This provided a means for evaluating results and determining the validity of the pressure measurements. Measurements which differed greatly from those of nearby gages were analyzed to determine if the difference resulted from reflections or gage malfunctions. Readings which were significantly different with adjacent gages or repetitive tests of the same gage were not included in calculation of average maximum pressures.

Phase I

Reflected pressures

Results of Phase I testing are shown in Table 1. Reflected pressures were measured at eight gage locations along the reflecting wall to allow a comparison with Pr values predicted using Figure 4.6 of Reference 1. Figure 5 shows reflected pressure measurements versus scaled distance for gages 1 to 4 which are directly in front of the donor bay. These measurements are bounded by Pr and 1.75*Pr for scaled distances of 5 to 20 ft/lb**1/3. The 1.75 factor, although not applied as described in Chapter 4 of Reference 1, serves as a convenient multiplier to predict the maximum pressure expected at a gage.

Reflected pressures were also measured at each gage line in the acceptor bay. A 6"x3"x1/4" angle was used to provide a reflecting surface and was bolted to the floor so that the front face

was flush with the gage line. The pressure gages were installed in the angle 3" above the floor. This allowed measurement of the maximum effectual pressure in accordance with the criteria. At the face of the acceptor bay, the average reflected pressure for a center charge (location 4) was 17.4 psi. The average pressure at the center of the acceptor bay, gage line 3, was 12.8 psi. With the charge located an equivalent of three feet off of the common wall and six feet from the front of the bay (location 9), the average pressure at the front and center of the acceptor bay were 17.0 and 9.9 psi respectively. One test was run with the charge located at the extreme front corner of the bay (location 8) to determine the worst case pressures even though this is not a credible configuration. Pressures for this test average 25.4 psi at the face of the acceptor bay.

Reflected pressure versus scaled distance is plotted for several charge locations in Figures 6 and 7. These curves represent the measurements taken at the first and third gage lines in the acceptor bay with the reflecting front wall in place. Most of the gages parallel the Pr curve from Reference 1 and are roughly bounded by applying a 1.75 multiplier to this curve as was done for the front wall gages. Gages 10 and 11 however, do not follow this curve and actually show a rise in pressure with increasing scaled distance.

The distribution of pressure in the front half of the acceptor bay indicated that the common wall between the bays shielded areas close to the wall from reflected pressures. The exception to this was gage 9 which was located adjacent to the common wall but was also at the face of the bay and therefore was not shielded. The pressures measured next to the exterior wall were higher than at locations in the center of the bay because of the reflection of the pressure wave on the wall. These two phenomena caused a distribution of pressure which actually increased with distance from the charge in some cases.

When the front wall and roof were removed, reflected pressures at the first gage line averaged 7.5 psi for a center charge. This indicates that the pressures reflected by the wall are approximately 10 psi higher than the wrap around pressures. For charges located closer to the front of the bay, the difference between pressures with the reflecting wall in place and pressures with it removed decreased. This was due to the increasing influence of wrap around and direct pressures as the charge was moved forward.

The back wall of the donor bay on the model was removed for some tests to allow the charge to be placed in the rear half of the bay. This also allowed comparison of pressure measurements with the wall in place and with it removed. This was done to determine the effects of back wall reflections. Some increase in pressure

was observed with the back wall in place; however, additional testing will be required to determine a valid method for predicting this increase. In all cases, removal of the back wall to model the "thru" bay condition resulted in pressures equal to or less than the 3-wall cubicle configuration.

Side-on pressures

Side-on pressures were measured only in the acceptor bay. These pressures were measured to examine the relationship between side-on and reflected pressures in the model. These pressures were also useful in determining the actual pressures personnel would be exposed to during a detonation. The most probable configuration in a bay is personnel located away from reflecting surfaces, such as a wall, and thus not subjected to the higher reflected pressures.

Pressures along the first gage averaged 10.4 psi for a charge located in the center of the donor bay (location 4). When the charge was moved to the front (location 9), the pressures increased to an average of 12.2 psi. Removal of the front wall and roof reduced the average pressure to 7.5 psi for a center charge and 9.3 psi for a front position charge.

All side-on pressures measured in the acceptor bay were less than 15 psi except when the charge was placed at the face of the donor bay. For these locations, the acceptor gages were directly across from the charge and were not shielded at all by the common wall. When side-on pressures are compared to reflected pressures, the ratio is less than predicted in the literature (1,2). A definite explanation for this was not determined, however it is most likely due to the obliquity of the reflecting angle to the pressure wave.

Phase II

Reflected pressures

The results of Phase II testing are shown in Table 2. This table contains reflected pressures measured at the first two gage lines. The maximum average pressure recorded was 13.8 psi for a center charge at gage line one and 10.5 psi at gage line two. The pressures measured for a charge located in the front corner of the bay were slightly less than the center charge. It presumed that this is due to a higher wall velocity for the front charge resulting in less pressure being reflected. The additional time that the gypsum board remained in place relative to the plywood produced slightly greater pressures reflected into the acceptor bay.

Charge location 13 was used in Phase II to measure pressures for the DBA charge location which was three feet from the common wall and three feet from the face of the donor bay. This configuration produced an average reflected pressure of 9.1 psi.

Side-on pressures

Pressures measured at gage line one for the polyethylene wall averaged 7.7 psi for a center charge and 11.0 for a front charge. Pressures for the plywood wall for center and front charge locations measured 8.2 and 10.8 respectively. When the gypsum board was installed the pressures increased to 8.7 for the center charge location and decreased slightly to 10.1 for the front charge.

Wall response

The polyethylene sheared along the edges for both tests with no tensile failure over the surface. Although the time that the polyethylene remained in place was not known it was presumed to be very short because of the mode of failure. Pressures measured with this material in place were slightly higher than pressures with no reflecting wall at all.

The plywood was displaced enough to clear the extension of the floor of the model and was lying on the floor of the chamber after the test. A crack had formed along the yield line with a permanent deflection of approximately one inch. This response showed that the plywood remained in place long enough to develop a significant portion of its bending resistance and therefore was able to reflect pressures. Reflected pressures for the plywood were slightly higher than the polyethylene for a center charge and significantly higher for a charge located near the front of the bay.

The gypsum board material, as expected, reflected more pressure into the acceptor bay than the other materials. In the first test, with a close spacing of fasteners, the gypsum board had a permanent deflection of 1/8 inch. The displacement in the second test with a six inch nail spacing was approximately 1/2 inch. The gypsum board split the length of the wall at mid-height for the remainder of the tests with a single nail at the top. This indicates that the board remained in place long enough to develop some bending but only because of its mass and not the supports. The effects of wall mass on reflected pressures are shown in Figure 8 for gages at the second line.

Analysis

The principal objective of this test program was to determine whether or not personnel protection requirements were being met. The criteria requires that maximal effective pressures in adjacent occupied areas be less than 15 psi. For both center and front charge locations in Phase I, the average reflected pressure exceeded the maximum allowable by the criteria by about 2.5 psi. Although this is a small disparity it is not technically acceptable. In addition, some individual gage measurements were much higher than the average. The explosives limits had already been reduced as much as possible and continuation of the operations would require an exemption from the criteria for the duration. Three alternatives were considered to resolve the problem. The first was to change the DBA to take advantage of the actual configuration in the bay. The operations in the explosives facilities are performed on work benches and fixed equipment at several locations in a bay. Only a portion of the total HE weight in the bay is located at any given work location. This makes the DBA very conservative since it assumes that the entire explosives limit will be placed in the worst possible location. The center of these charges as a group is likely to be between the center of the bay and the back wall. This makes the center bay charge location a suitable configuration for evaluating the true overpressure hazard. The disadvantage of this alternative was that it reduced the flexibility of the operations and required strict administrative control to ensure that the explosives weights and locations chosen were not changed. This alternative was eliminated because of these disadvantages. The second alternative was to file for an exemption of the 15 psi requirement for these operations. This alternative was eliminated because it was desirable to operate without an exemption wherever possible. The third alternative was to continue the test program to model the actual reflecting wall response and determine the actual pressures. This alternative was chosen and Phase II was initiated.

A secondary objective of the test program was to develop a method of predicting overpressures in similar facilities. Several attempts were made to predict pressures in the acceptor bay using various multipliers on the charge weight, total scaled distance to the point of interest, and Figure 2-15, Ref. 2. These were not successful mainly due to a lack of correlation in the data for some of the gages, ie. increasing pressure with increasing distance. The method chosen, based on the available data, was to multiply the reflected pressure predicted by using Figure 2-15 of Reference 2 by 1.75. The scaled distance was equal to the distance from the charge to the reflecting wall plus the distance to the point of interest divided by the cubed root of the charge weight. This method provided a reasonable upper bound for the pressure. Another alternative for predicting pressures was to produce graphs relating pressure to: scaled distance to the

reflecting surface, angle of obliquity, and scaled distance from the reflecting surface to the point of interest. Additional testing with variations in charge weight and location would be required to establish meaningful values for this method.

Conclusions

The results of Phase II testing support the assumption that when the response of the clay tile wall is modeled, the pressures reflecting into adjacent acceptor bays are below 15 psi. This will allow the operations to continue without the need for an exemption from the criteria. The test program produced a method for determining an estimate on the maximum pressures in adjacent bays for facilities with this configuration.

Application

The results of the test program will be used to verify compliance with protection requirements for a particular facility; however, a large number of facilities in use today have similar geometries, construction, and explosives limits. Variations in charge weight, charge location, and gage positioning used in this test will allow prediction of pressures in many of these facilities in which the protection provided is not accurately known. Many times explosives limits are set artificially low because these values are not available; however, there will also be instances in which limits will have to be lowered based on the results of this test program. Results of the tests can also be used to reduce personnel exposure by allowing evaluation of restrictions on HE location in a donor bay and physical barriers for personnel in critical locations of an acceptor bay.

SUMMARY

Test Plan

The test program provided a means for evaluating personnel exposure to hazardous overpressures for a particular configuration of explosives operations bays. Existing methods for accurately determining pressures which are reflected into adjacent bays have not been previously available. This has resulted in the use of simplifying, conservative assumptions to predict these pressures. The test plan varied charge location, gage position, and reflective surface configuration to accurately measure reflected and side-on pressures.

Results

The measured pressures for the most realistic charge location indicated that protection requirements were not met for the rigid wall configuration used in Phase I. Pressure measurements which were above the limits were concentrated in the front portion of the acceptor bay. When the response characteristics of the clay tile wall were incorporated into the model, the pressure measurements were in strict compliance with the criteria.

Application

The abundance of facilities with a similar configuration necessitated the variation of charge location and gage positioning to allow application of the results to other operating bays. The methods for determining pressures for other charge weights will be developed during later testing. The results will be used to set HE limits and evaluate personnel protection in other facilities.

Future Testing

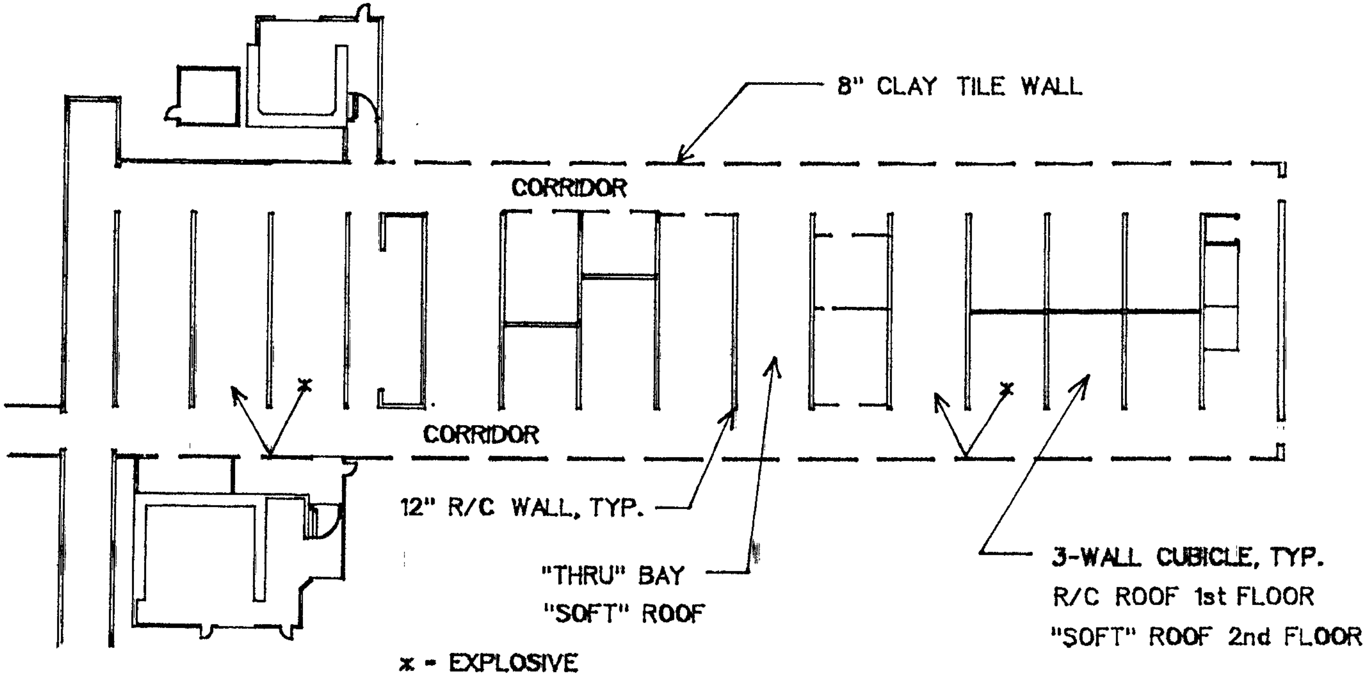
Currently 60 test shots have been made and the first two phases have been completed. The configurations tested were used to establish boundaries for pressure measurements and to determine critical locations. The most obvious need for further testing is variation in the charge weight to expand the applicability of the results.

Other tests planned for the program include determination of back wall effects on the reflected pressures. Phase I results indicated that pressures reflecting off the back wall became significant when the charge was placed between the center and back of the bay. Incorporation of this effect into the prediction method could be a significant improvement.
Determination of leakage pressures from this type of facility is also an important consideration. A follow on phase of the project is planned to determine the pressures transmitted down the open corridor connecting the bays.

REFERENCES

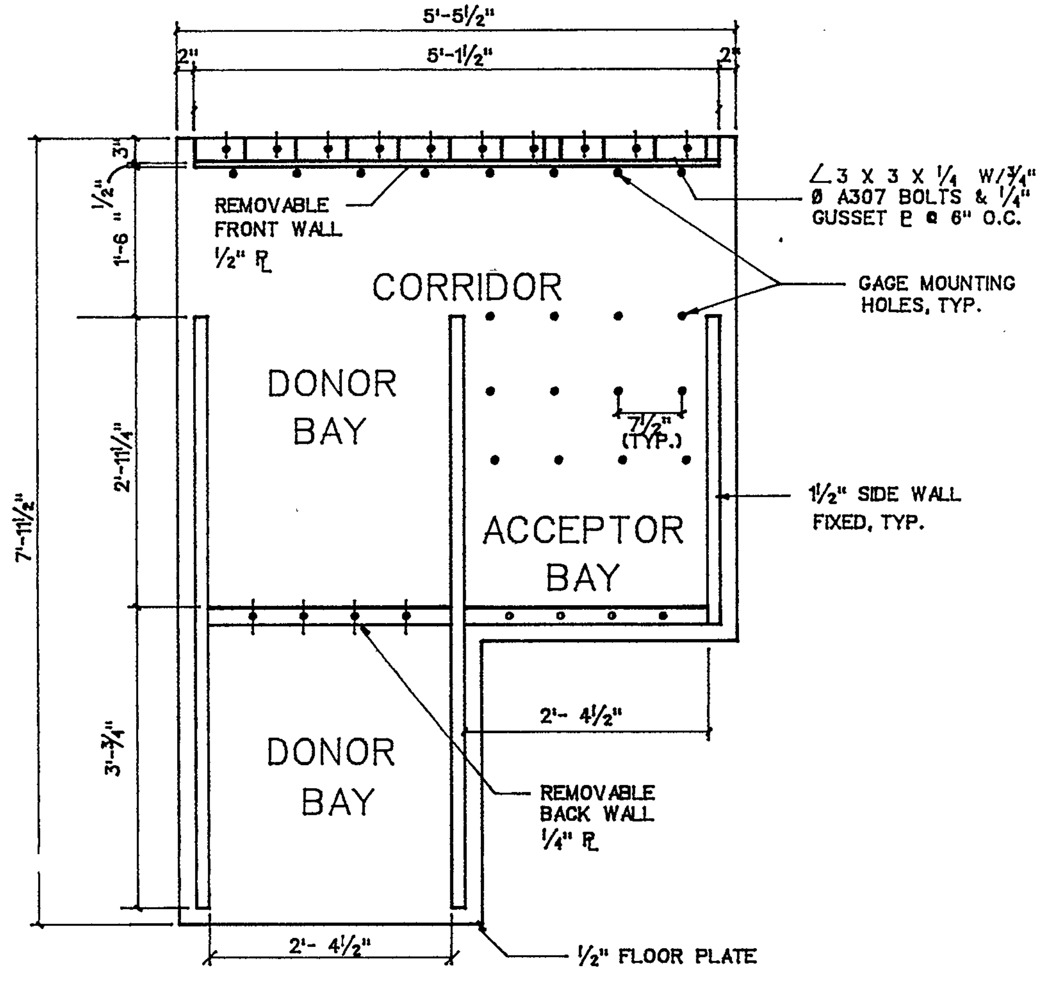
1. A Manual For the Prediction of Blast and Fragment Loadings on Structures, Department of Energy Technical Manual DOE/TIC-11268, Nov. 1989.

2. Structures to Resist the Effects of Accidental Explosions, Volume II, Blast, Fragment, and Shock Loads, Department of the Army Special Publication ARLCD-SP-84001, Dec. 1986.



TYPICAL EXPLOSIVES OPERATING BUILDING

FIGURE 1



PLAN VIEW
(ROOF PL NOT SHOWN)
SCALE: 1" = 1'- 0"

FIGURE 2

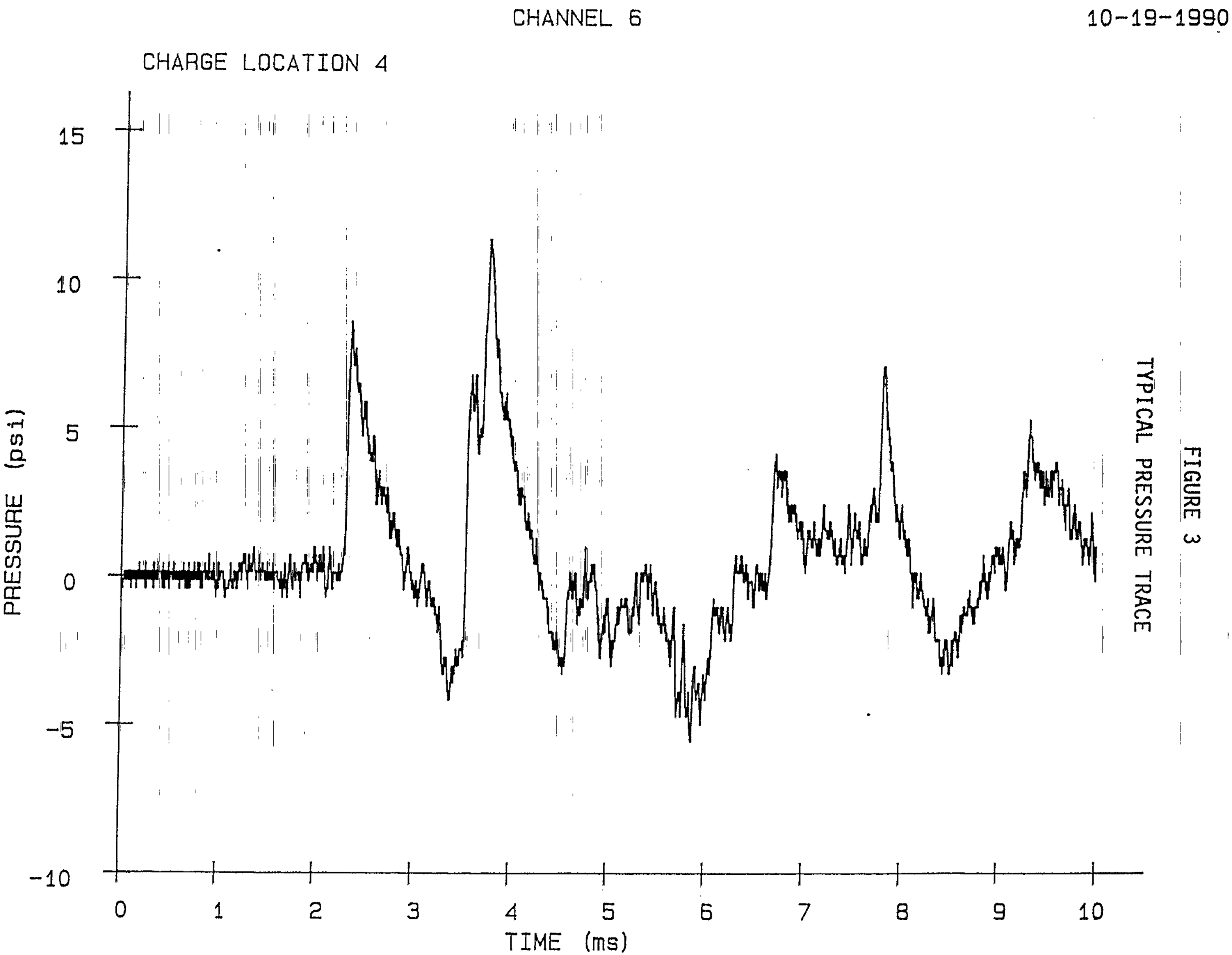


FIGURE 3
TYPICAL PRESSURE TRACE

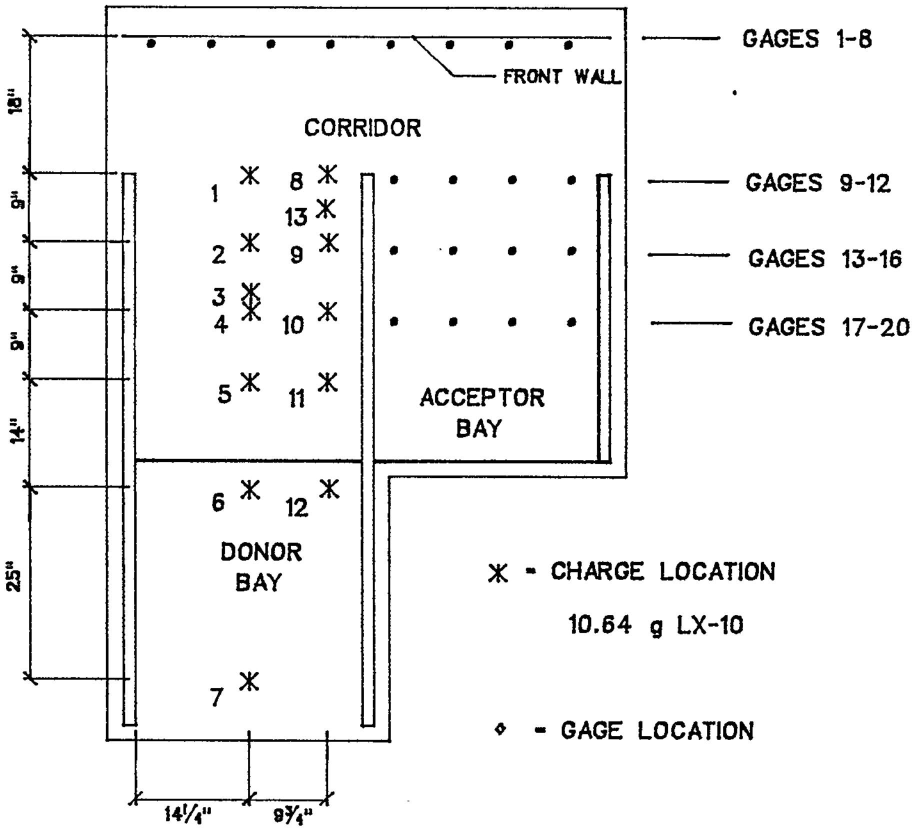


Figure 4 CHARGE LOCATIONS

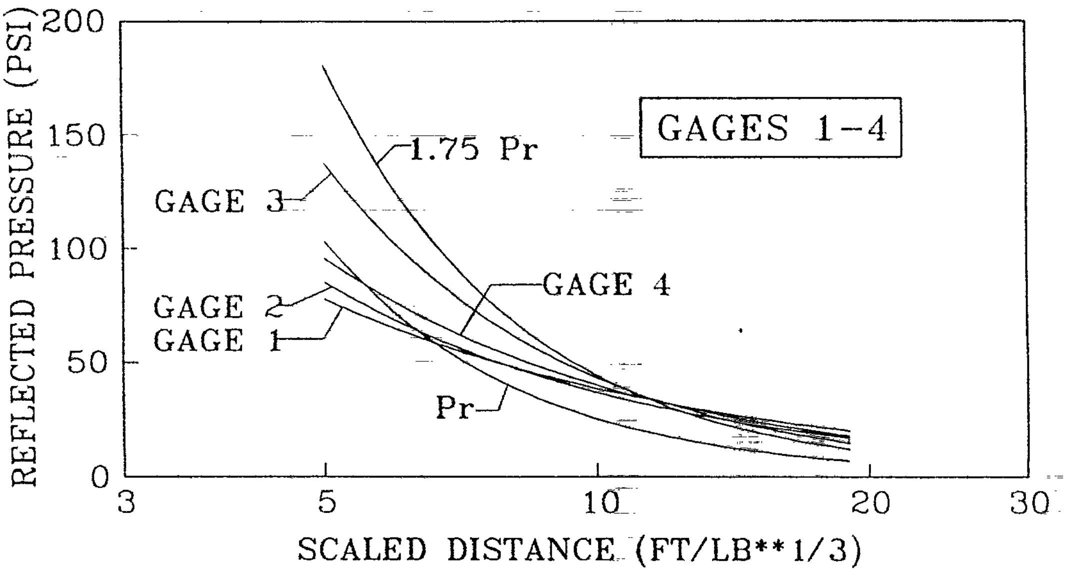


FIGURE 5 REFLECTED PRESSURES AT WALL

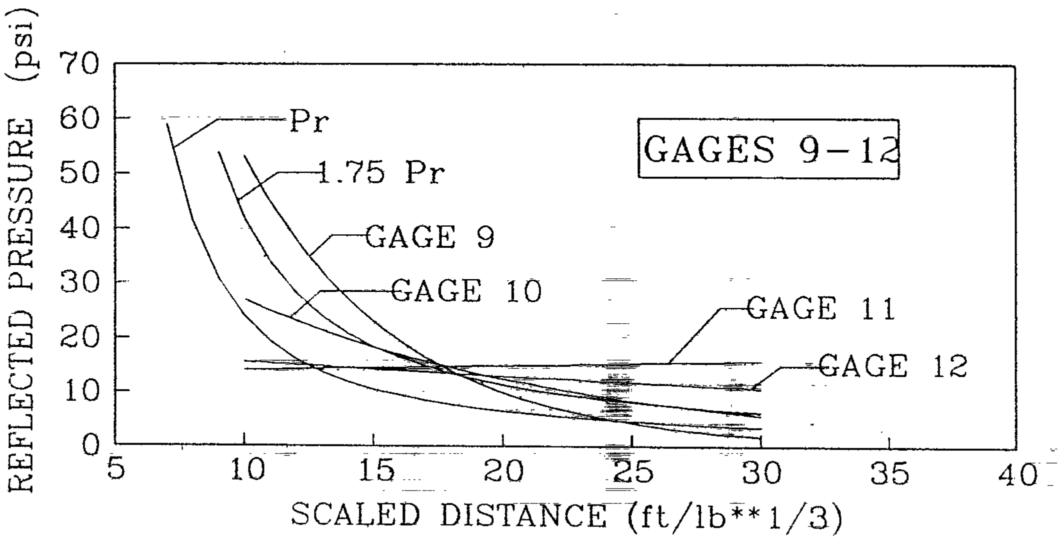


FIGURE 6 REFLECTED PRESSURES IN ACCEPTOR BAY

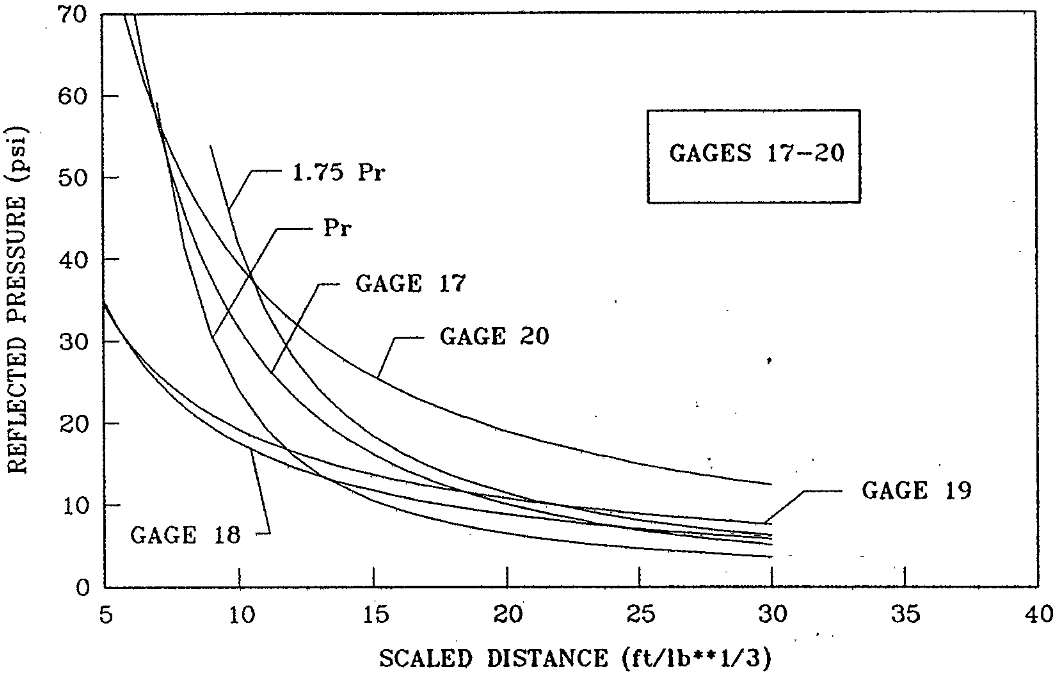


FIGURE 7 REFLECTED PRESSURES ACCEPTOR BAY

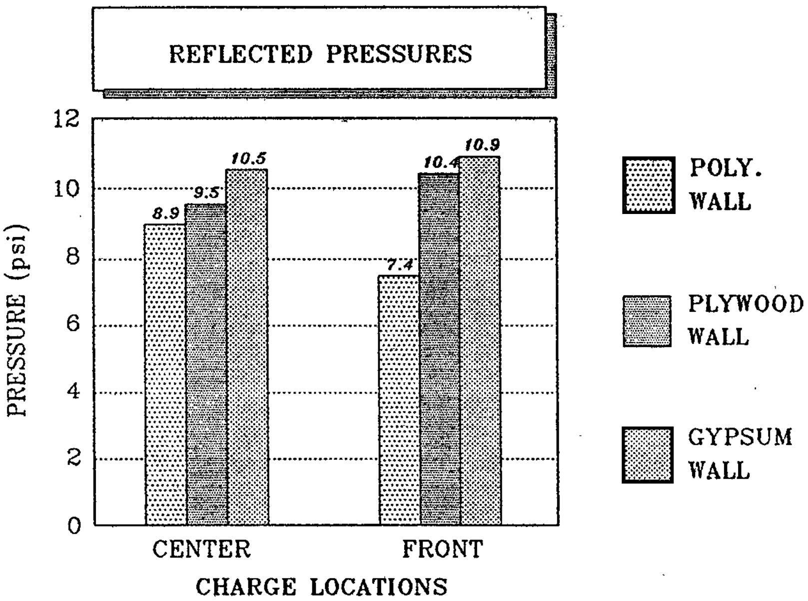


FIGURE 8 WALL RESPONSE EFFECTS

PHASE I

TYPE	LINE	MEASURED	Pr CURVE (**)
REFLECTED	1	17.4	7.7
REFLECTED	3	12.8	5.3
SIDE–ON	1	10.4	3.5
SIDE–ON	3	8.3	2.5

(CHARGE LOCATION 4)

* AVERAGE REFLECTED PRESSURES AT 1st GAGE LINE > 15 PSI FOR ALL CHARGE LOCATIONS IN FRONT HALF OF DONOR BAY

* IF FRONT WALL IS REMOVED, ALL PRESSURES < 15 PSI FOR ALL CHARGE LOCATIONS EXCEPT FACE OF DONOR BAY

** REFLECTED PRESSURE FROM FIG. 2–15, REF. 2

TABLE 1 PHASE I RESULTS

PHASE II

REFLECTED PRESSURES

CHARGE LOCATION	MATERIAL	GAGE LINE	PRESSURE (PSI)
CENTER	POLY.	2	8.9
FRONT CORNER		2	7.4
CENTER	PLY.	2	9.5
FRONT CORNER		2	10.4
CENTER	GYP.	1	13.8
		2	10.5
FRONT CORNER		1	9.1
		2	10.9

CENTER = LOC. 4 FRONT = LOC. 9

TABLE 2 RESULTS PHASE II